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Land Locomotion Laboratory
Research Division
Research and Engineering Directorate

A PRELIMINARY ANALYSIS OF THE FORCE SYSTEM ACTING ON A RIGID WHEEL

By

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ABSTRACT

Normal pressure distribution measurements under rigid wheeels operating in sand and loam are reported in this paper. The effect of frictional (tangential) forces are also considered by means of the "Friction Circle Method". Experimental results justify the practicability of the theoretical assumption made. The necessary direction of further research is outlined.

ACKNOWLEDGEMENT

This study was performed under the supervision of Major R. A. Liston, Chief of the Land Locomotion Laboratory and Mr. Z. Janosi, Chief of the Theoretical Land Locomotion Mechanics Section of the Land Locomotion Laboratory.

Professor R. M. Haythornthwaite of the University of Michigan reviewed the work and gave very useful suggestions.

Messrs. A. J. Rymiszewski, D. Spore and J. Lauro were responsible for the instrumentation.

Professor Wesley F. Buchele of Michigan State University provided the pressure cells used in the experimental phase of this work.

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INTRODUCTION:

The problem of describing the resistance of a moving wheel is a very old one. Many investigators have attempted to define the nature of forces acting on a rigid wheel moving in deformable media and the pressure distribution along the contact area. Some of the earlier investigators were Bernstein[1], Letoshnev[2], and Goriatchkin[3], who treated the problem of rigid wheels in soft ground analytically and proposed an exponential equation for the description of pressure (p) versus sinkage (z) relationships in the form of

$$p = kz^n \qquad \ldots\ldots 1$$

where k and n are parameters which vary, depending upon the soil used by the investigator[4].

Bekker[5], generalized the above relationship by introducing

$$k = \frac{k_c}{b} + k_\phi \qquad \ldots\ldots 2$$

where k_c is the cohesive and k_ϕ is the frictional modulus of deformation; b is the smaller dimension of a bearing plate; and n is a soil parameter.

Recently contributions by Vincent[6], Phillips[7], Sohne[8,24], Reece[9], Schuring[25], Tanaka[10], the Land Locomotion Laboratory[11, 12, 13, 14, 22], and possibly by many others helped to obtain a better understanding of the wheel-soil interaction. Despite the effort spent by researchers, few analytical equations exist. At present (1962) there is much to be done toward the refinement of existing pressure distribution, motion resistance equations[11].

The semi-empirical equation 1, with parameters in equation 2, which has been generally accepted in Land Locomotion Mechanics, was established on the basis of the stress-strain relationship suggested by plate penetration tests[4].

The pressure distribution under a plate was taken to describe the pressure distribution under wheels. Therefore, this equation will have limitations, especially when applied to wheels of small diameter because of the rapidly increasing difference between the arc length of a wheel and the corresponding chord length. The idea gives good results for wheels having diameters over 30 inches[16].

The accurate definition of the pressure distribution beneath a wheel is very important from sinkage and consequently motion resistance point of view. However, the use of the exponential form of equation 1 in wheel equation has several disadvantages:

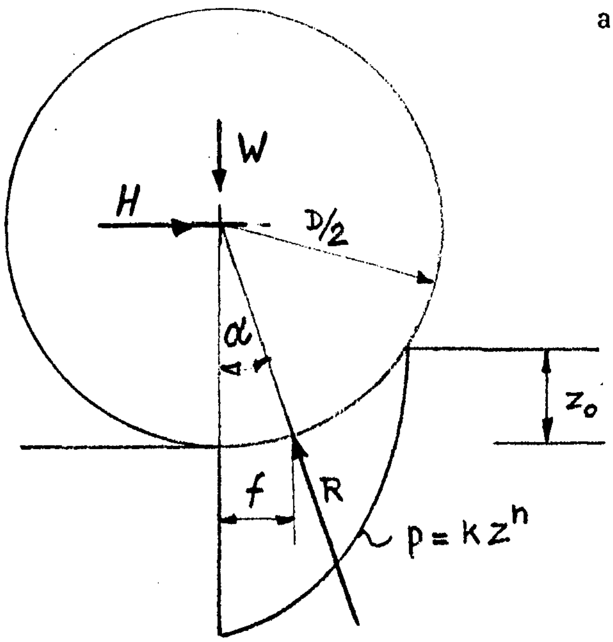


Figure 1: Equilibrium of a Rigid Wheel with $p = kz^n$ Pressure Distribution.

a. It assumes a discontinuity at the point of maximum sinkage. (Figure 1). Experiments indicate that because of the flow of granular soils and the expansion of cohesive soils, the pressure distribution extends beyond the tow of the wheel and reaches its peak ahead of that point[6,15,17].

b. The assumed pressure distribution diagram unfavorably influences the position of the resultant, which is a direct function of the motion resist-ance. (Figure 1).

$$H = \frac{Wf}{D/2 \cos\alpha}$$

c. It does not include the slip sinkage relationship.

d. The tangential forces are neglected.

Janosi[11], has developed a new approach to the wheel equation that utilizes the normal stress distribution of equation (1).

The purpose of the work reported here was to improve the accuracy of his traction vs. slip relationship by considering the true normal pressure distribution. By analysis of pressure distributions obtained experimentally the effect of tangential forces are also considered. At this point these results have not been applied to Janosi's work.

The "Friction Circle Method" known from soil mechanics has been used to analyze the frictional forces under a rigid wheel for the first time in this paper. In order to simplify the analysis, the coefficient of friction has been assumed to be constant along the contact surface. This implies that slip occurs throughout the wheel contact length. Furthermore, the approximation is introduced that the resultant elementary soil reaction always acts at angle ϕ to the local normal of the wheel. Until further experimental evidence is gained, these assumptions are accepted to be valid for a wide range of slip conditions, especially when the contact area is small.

The theoretical part of this work deals with the system of forces acting on a rigid wheel while the experimental part is directed toward the establishment of the position of the resultant soil reaction vector as a function of slip, sinkage, soil properties and load.

No attempt has been made to correlate the theory with experimental data at this time, The graphical integration of the measured normal stresses and the calculated tangential forces, however, satisfy equilibrium conditions with good accuracy, which indicates that the assumptions made are sound. Thus, the present approach has been judged promisingand the extension of this investigation is undertaken at the present time.

EQUATIONS OF EQUILIBRIUM:

In order to define the motion resistance of a wheel moving in soft ground, the forces acting against the wheel have to be defined. This system of forces must satisfy static equilibrium conditions. The force system of driven, braked, and towed wheels will be discussed here in detail.

(1) Driven Wheels: The wheel is driven, when a moment (M) is imposed upon the wheel in the direction of the motion. The wheel will have a tendency to slide relative to the ground, depending upon the magnitude of applied torque. The shearing forces (dT)* on an arbitrarily chosen elementary contact area (dA) will oppose the motion (Figure 2). From geometry, the elementary normal force (dN) passes through the center of the wheel. By adding dN to dT, dR must act at ϕ relative to dN when failure occurs[20]. ϕ is defined as the friction angle and may take one of two possible values.

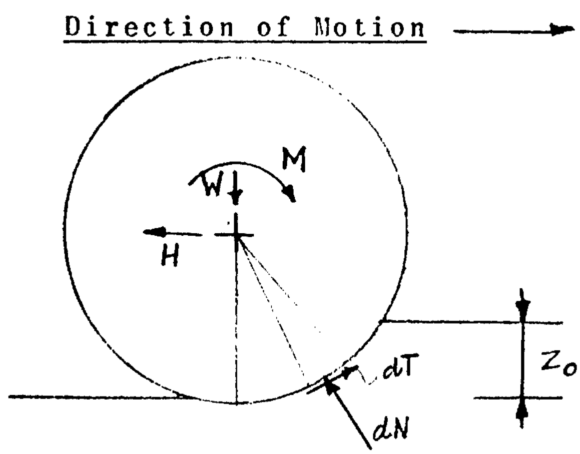


Figure 2: Ground Reaction on an Elementary Area

*dT here refers to the frictional part of the tangential forces only.

When the angle of internal friction of the soil is greater than the interface friction of the soil and wheel, ϕ refers to the friction between the wheel and soil. When the angle of internal friction is smaller than the interface friction angle, ϕ refers to the angle of internal friction. In other words, the smaller value of the friction angle between soil and wheel or the friction angle between soil and soil will be assigned to ϕ, depending on whether slip or soil failure is most likely to occur. Constructing dR at several locations along the contact area, assuming that ϕ is constant along the contact length, it can be visualized that the elementary resultants will be tangent to a circle of radius $r = \frac{D}{2} \sin \phi$, commonly called the friction circle[18,19]. Under these conditions it may be safely assumed that the resultant (R) of the elementary reactions will also be tangent to the friction circle[21]. (Figure 3).

The vertical load (W) and the drawbar load (H) act at the center of the hub of the wheel where the load is transmitted from the chassis. (Figure 3). In soils possessing cohesive properties, the affect of cohesion along the contact area has to be also considered.

Taking: $K = Ac$

Where A is the ground contact area
c is the cohesive stress
K is the cohesive force

The equations of equilibrium for the force system acting on the wheel may be written as follows:

Case a: $\phi \neq o \quad c \neq o$

$$\Sigma M_o = M - rR - K\frac{D}{2} = 0$$

Direction of Motion ⟶

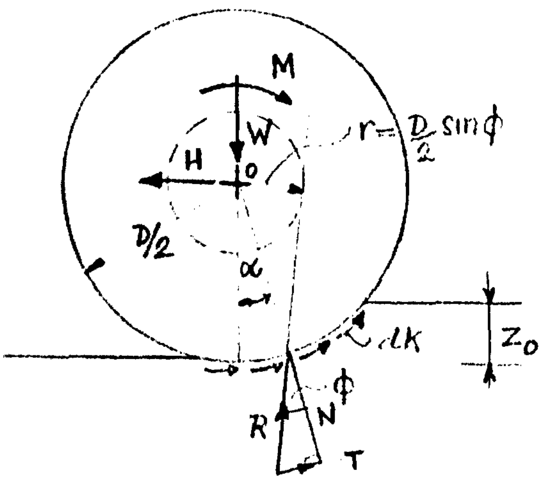


Figure 3: Equilibrium of a Driven Wheel.

$$\Sigma z_i = W - R\cos(\phi - \alpha) - z_o \, bc^{**} = 0$$

$$\Sigma x_i = R\sin(\phi - \alpha) - H + \sqrt{Dz_o - z^2}.bc^{**} = 0$$

$$\ldots\ldots\ldots 3$$

Where b is width of wheel.

Case b: $\phi \neq o \quad c = o$

$$M - rR = 0$$

$$W - R\cos(\phi - \alpha) = 0$$

$$R\sin(\phi - \alpha) - H = 0$$

$$\ldots\ldots\ldots 4$$

Case c: $\phi = o \quad c \neq o$

$$M - K\frac{D}{2} = 0$$

$$W - R\cos\alpha - z_o \, bc^{**} = 0$$

$$R\sin\alpha - H + \sqrt{Dz_o - z^2}. \, bc^{**} = 0$$

$$\ldots\ldots\ldots 5$$

Once α is know in the above equations, the remaining unknowns can easily be determined.

**Terms marked with asterisks approximate the projection of the contact area.

(2) Braked Wheels: If a moment (M) is applied to the wheel in an opposite sens to the direction of the motion, the wheel is braked. The sense of the frictional forces also will reverse. When failure occurs, the resultant will be tangent to the friction circle at the left. The equilibrium of the wheel may be formed as follows:

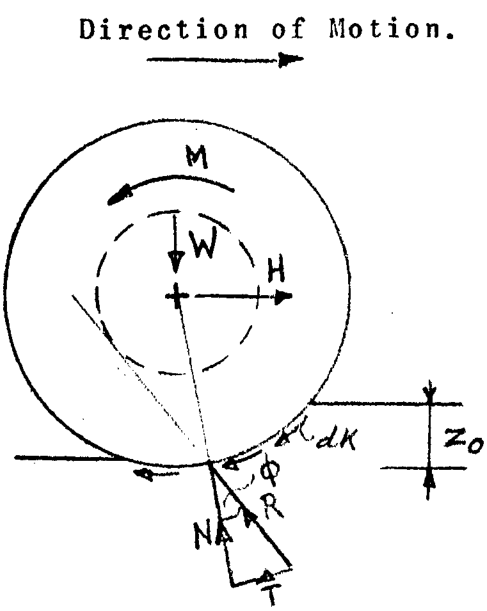


Figure 4: Equilibrium of a Braked Wheel.

Case a: $\phi \neq o$ $\quad c \neq o$

$$\Sigma M_o = Rr - M + K\frac{D}{2} = 0$$

$$\Sigma z_i = W - R\cos(\alpha + \phi) + z_o \, bc^{**} = 0$$

$$\Sigma x_i = H - R\sin(\alpha + \phi) - \sqrt{Dz_o - z_o^2} \, . cb = 0 \qquad \ldots\ldots 6$$

Case b: $\phi \neq o$ $\quad c = o$

$$Rr - M = 0$$

$$W - R\cos(\alpha + \phi) = 0$$

$$H - R\sin(\alpha + \phi) = 0 \qquad \ldots\ldots 7$$

Case c: $\phi = o$ $\quad c \neq o$

$$K\frac{D}{2} - M = 0$$

$$W - R\cos\alpha + z \, bc^{**} = 0$$

$$H - R\sin\alpha - \sqrt{Dz_o - z_o^2} \, cb^{**} = 0 \qquad \ldots\ldots 8$$

Again the knowledge of α furnishes the key for the solution of equations 6, 7 and 8.

**Terms marked with asterisks approximate the projection of the contact area.

(3) Towed Wheels: The case of the towed wheel is very similar to that of the braked wheel. A towed wheel usually moves with a certain magnitude of negative slip, therefore, a moment opposite sense that of the direction of the motion must be present. The equilibrium of the wheel can be expressed as in equations 6, 7 and 8.

TEST FACILITIES AND PROCEDURES:

In order to obtain actual pressure distribution curves for rigid wheels under variable loading and slip conditions a special apparatus was built. (Figure 5). Test apparatus consisted of a test wheel of 20" diameter and 3" width. Pressure cells, developed by students at the Michigan State University under the guidance of Professor Wesley F. Buchele[26], were embedded in the wheel face in such a way that pressure normal to the wheel would be measured. (Figure 6). The wheel was mounted on a dynamometer carriage. (Figure 5). A distributor was attached to the drive shaft of the wheel and produced a signal every 4.17^{o} of angular rotation of the wheel. (Figure 7). The linear displacement of the carriage was measured by means of a micro-switch attached to the driving sprocket of the carriage. (Figure 8). The wheel was loaded in 50 pound increments from 50 to 200 pounds. Wheel sinkage was measured by means of a sinkage-pot connected between the loading tray and the carriage. (Figure 9). The pressure cells, micro-switches and the sinkage-pot were connected to a series of analyzers and recorders. (Figure 5). The recorder continuously recorded the pressures acting against the wheel, the exact location of the load cells, the magnitude of linear displacements, and the sinkages. The pressure cells were calibrated by a device developing a known air pressure and have a maximum capacity of 20 psi. (Figure 10).

Tests were performed in sand and in a sandy-loam under laboratory conditions. Some important characteristics of the materials tested are tabulated below:

	SAND	SANDY LOAM
Moisture Content: W(%)	2.0	14.0
Density: γ (lb/ft^3)	103.0	78.0
Angle of Internal Friction: ϕ	28.0^0	22.0^0
Cohesion: c (psi)	0.1	1.1
Frictional Modulus of Deformation: k_ϕ	4.0	5.6
Cohesive Modulus of Deformation: k_c	0.0	9.0
Sinkage Exponent: n	1.0	0.5

Before the experiment the material was leveled with a leveling board attached to the carriage in order to assure a reference surface for sinkage measurements. Then the wheel was loaded and the experiment began by driving the wheel and the carriage simultaneously. After a complete revolution of the wheel, drag was applied to the carriage causing the carriage to slow down relative to the wheel and produce a different magnitude of slip. By increasing the drag on the carriage, pressure distribution measurements at higher slip were possible. The above technique was applied for testing at different slip-s since the speed of the carriage and wheel cannot be controlled separately. During the procedure, data were recorded continuously. The experimental technique produced data which permitted the plotting of normal pressure distribution and sinkage as a function of slip between 0 and 100% slip.

TEST RESULTS:

Samples of results of the series of experiments conducted pertaining to pressure distribution are presented here in chart form. The variation of pressure distribution under the 20" diameter and 3" wide test wheel is presented as a function of sinkage and slip.

Figures 11, 12 and 13 show the pressure distribution in sand under 150 pounds of vertical load at 0%, 56% and at 100% slip. The variation of pressure distribution for the same wheel and load at different slip percent is shown in Figures 14, 15 and 16. Note that the pressure distribution in the lateral direction is also shown in the figures.

Figures 17 and 18 illustrate the sinkage as a function of slip in sand as well as in farm soil.

Using the actual pressure distribution diagrams, the angle of inclination of the normal can easily be determined.

Figures 19 and 20 show the angular position of the normal force as a function of slip in dry sand as well as in sandy-loam.

Figures 21 and 22 indicate the magnitude of the experimental error involved in the measurements, when the axial load (W) is plotted against the vertical component of the normal (N), the vertical component of the ground reaction

(R_v), (R_v was evaluated by using the assumption, that R acts at ϕ with respect to the normal) and W. If the experimental error was zero, R_v would coincide with W.

Figure 23 shows the friction angle between the wheel material and sand, determined by means of simple sliding friction experiments.

For a material also possessing cohesive properties, the results of the sliding friction experiment will include the effects of both the friction angles and cohesion of the soil as a maximum value.

CONCLUSIONS:

1. The pressure distribution acting on a rigid wheel in a cohesionless material is a function of slip and sinkage. Increasing slip produces an increase in motion resistance. In order to maintain equilibrium of the force system, the pressure distribution becomes more skewed, that is, the resultant will have a higher angle of inclination with reference to the vertical.

2. The flow of sand in the case of cohesionless soils and perhaps, the expansion of the materials in case of soil possessing cohesive properties, has a great influence on pressure distribution. Its significance is increasing with higher slip %, however, even at zero slip the discontinuity of the pressure distribution diagram is not justified.

3. The pressure distribution across the wheel assumes a parabolic shape in sand, but in the case of cohesive soils, the outside pressure cells detect considerably higher pressure, than the one at the center of the wheel.

4. Sinkage is a function of slip in cohesionless soils since a soil transport phenomenon exists underneath the wheel. In the cohesive soil tested, the sinkage was independent of slip. The loam type of soil used in the experiment is highly compactable, therefore, the transportation of the soil by the wheel was not possible. In sand, the compaction effects are small, or none, under the load applied.

5. The angles of inclination of the normal as a function of slip shows characteristics similar to that of the sinkage slip relationship in both types of soil.

6. The effect of frictional forces on the wheel is sizable. It is essential to include the frictional forces in every wheel problem, because it is required to develop equilibrium. Inclusion of the frictional forces obtain a more correct definition of the force system acting on rigid wheels and can be best handled in terms of the friction circle and driving or braking moments.

7. In considering the frictional forces, the lower bound should always be selected for the angle of friction; that is, the smaller friction angle of the possible friction angles obtained from interaction of wheel and soil and soil and soil.

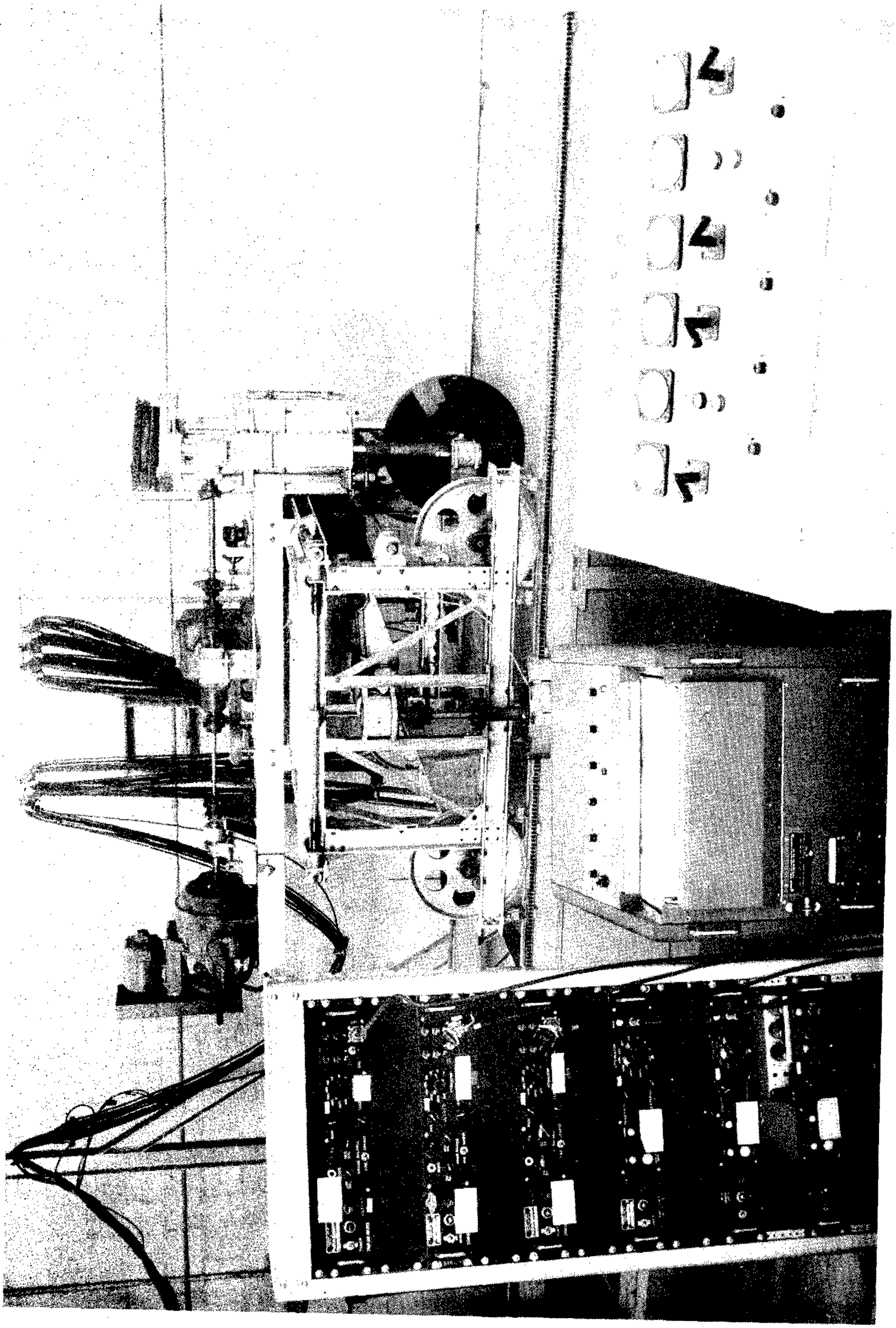
8. Knowledge of α is essential for the solution of the equilibrium equations for wheel in this approach. More experimental data is needed to define α analytically. The most essential part of future experiments is the determination of the minimum amount of cohesion when α is independent of slip. This problem appears to be analogous to the independence of slip-sinkage relationship. Future experiments also have to vary not only the soil properties but also the wheel geometries.

RECOMMENDATIONS:

1. It is recommended that experiments be continued to include variable wheel width in order to define the possible changes imposed by the changing wheel geometry on pressure distribution.

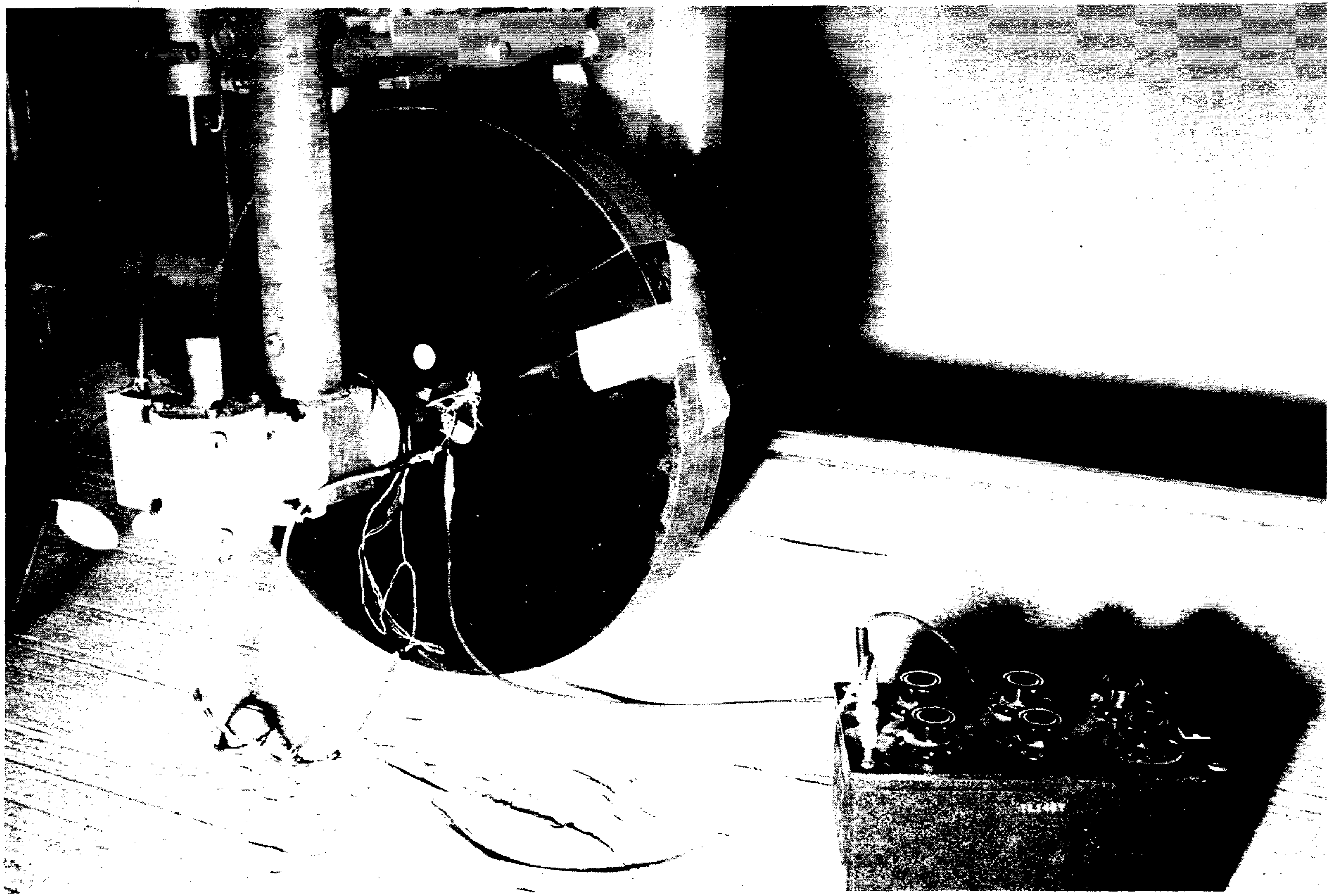
2. It is recommended that in addition to the original experimental data obtained in this investigation, the torque imposed upon the wheel also to be determined.

3. It is recommended that the minimum amount of cohesion producing independence of slip and sinkage be determined. This will establish the point at which the angle α (angle of inclination of the pressure distribution resultant with respect to the vertical) becomes independent of slip. To attain this goal, experiments with soils of variable friction and cohesion will be required.

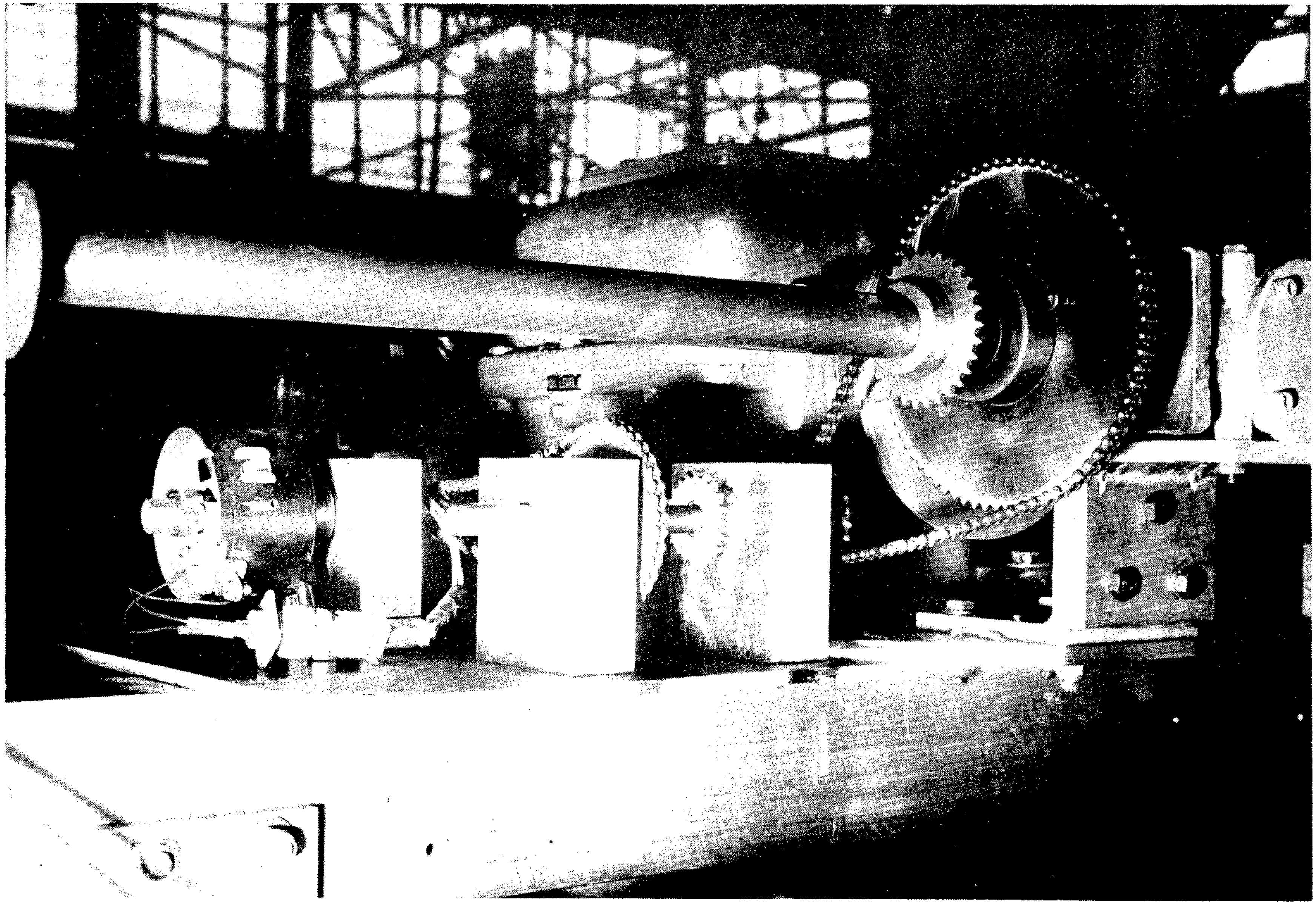


TEST APPARATUS

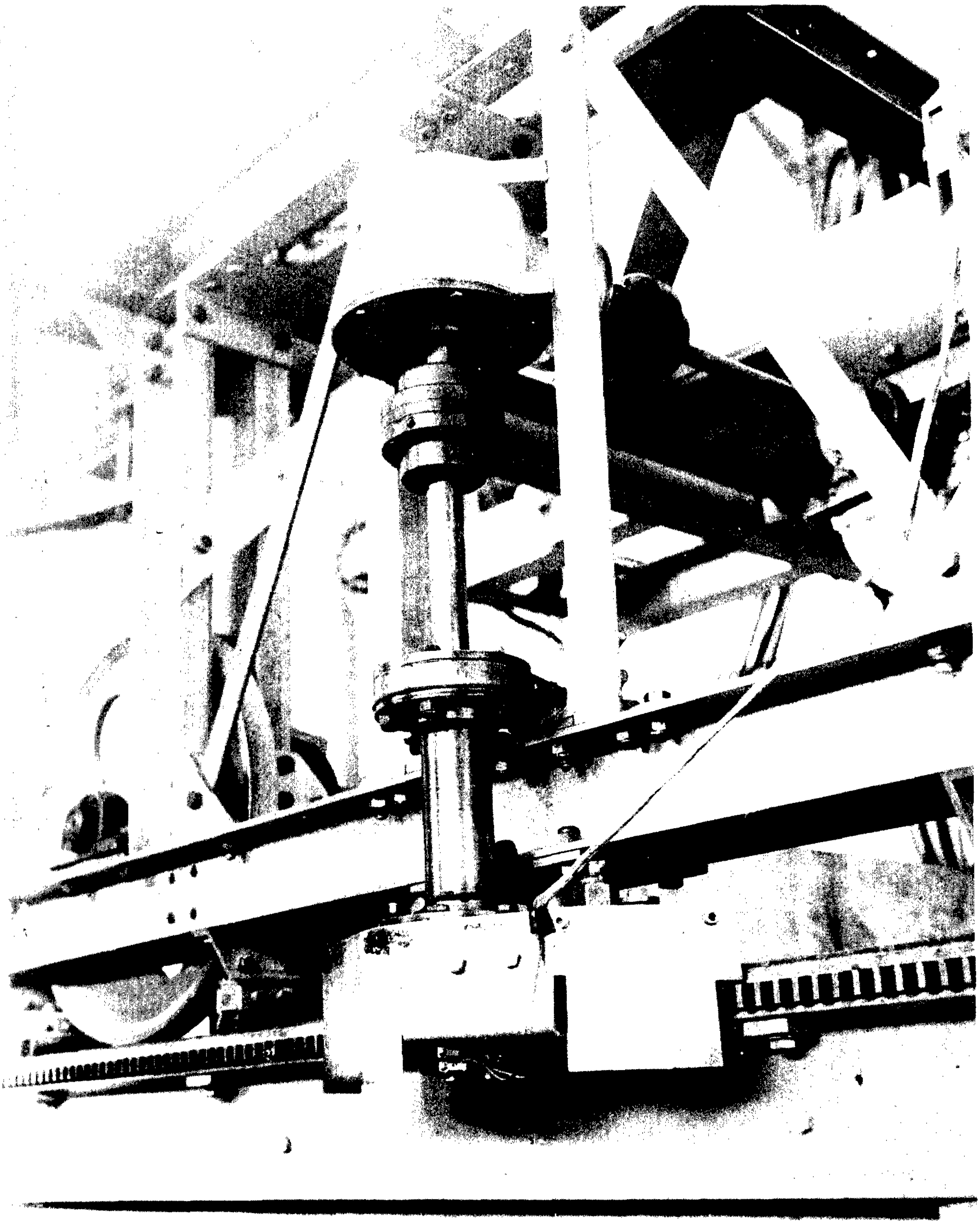
FIGURE No. 5



TEST WHEEL
FIGURE NO. 6

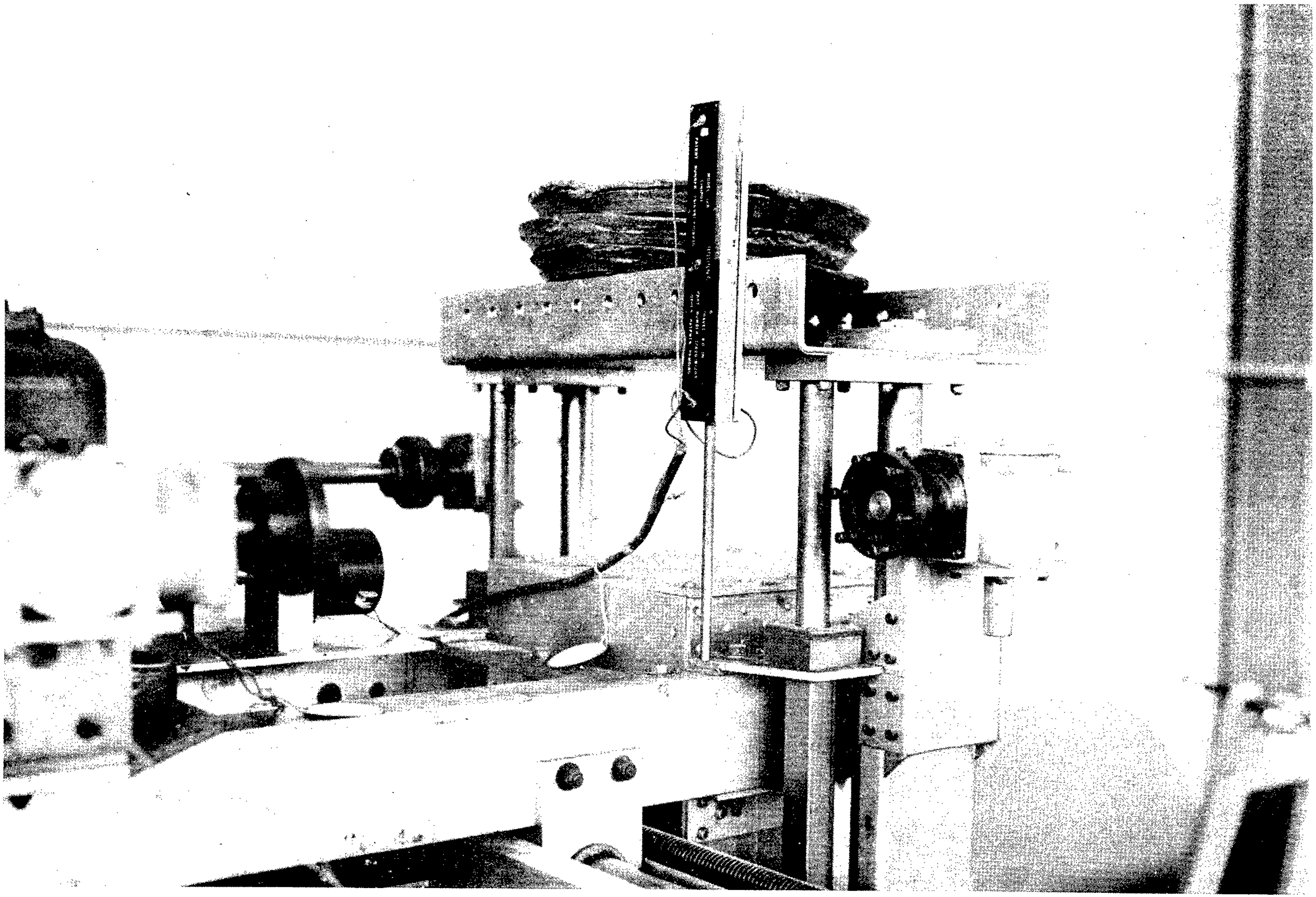


Device for the Measurement of Angular Displacement of the Wheel.
Figure No. 7



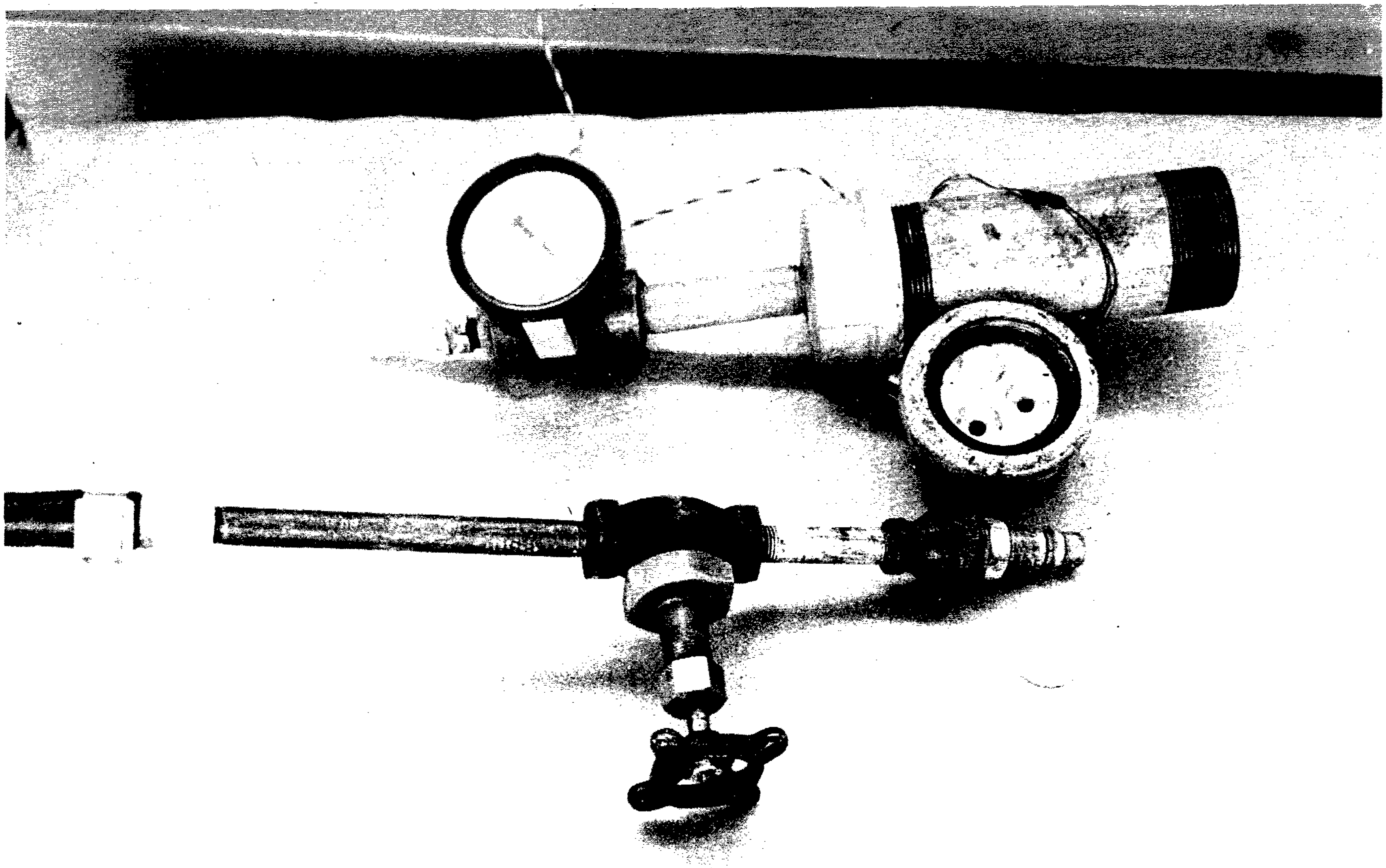
Device for the Measurement of Linear Displacement and Carriage Drive.

Figure No. 8



Sinkage Pot and Load Tray

Figure No. 9



Calibration of the Load Cells by Air Pressure.

Figure No. 10.

Pressure Distribution under a Rigid Wheel in Sand at 150 Lbs

Vertical Load and 0 % Slip.

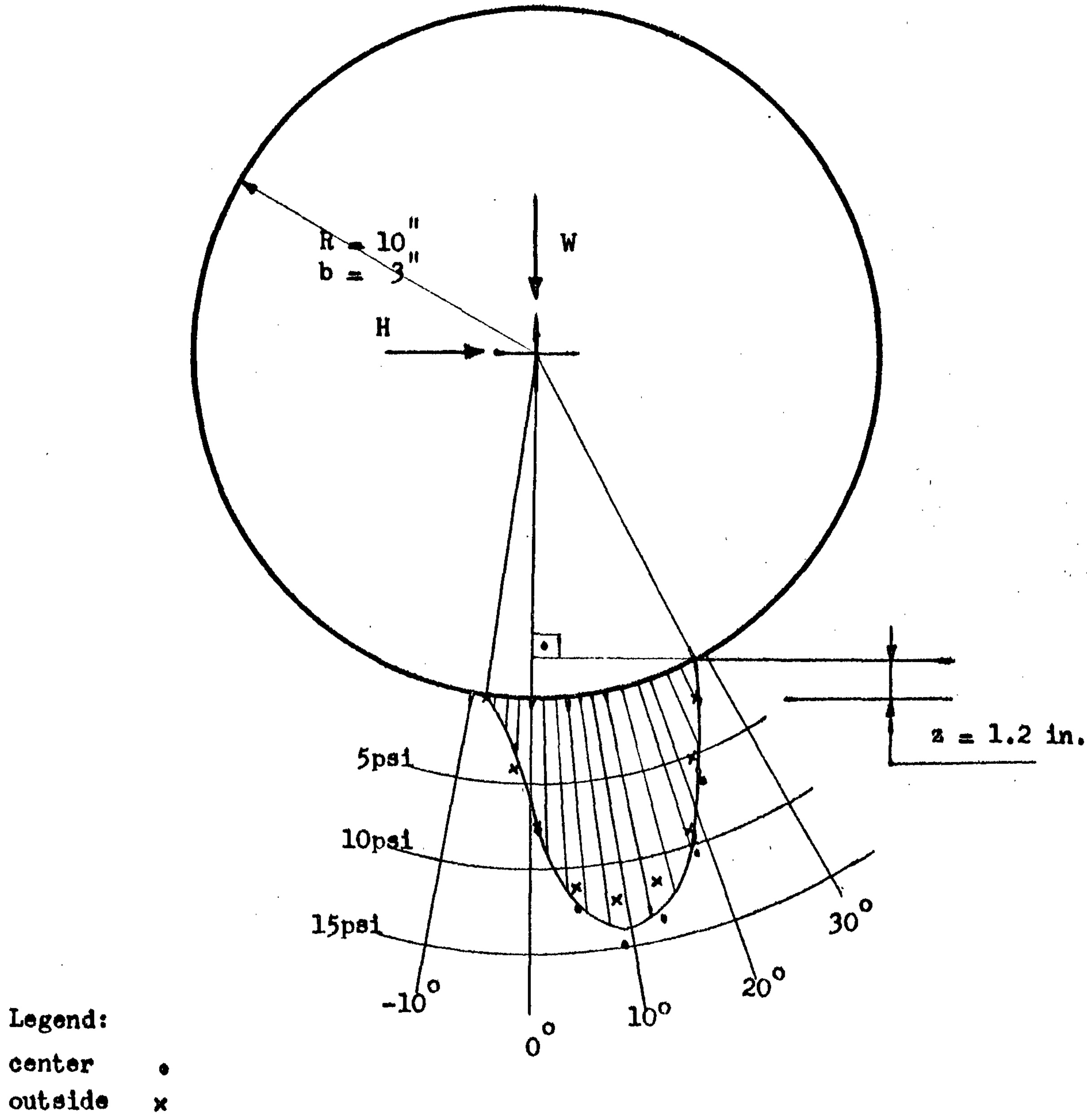
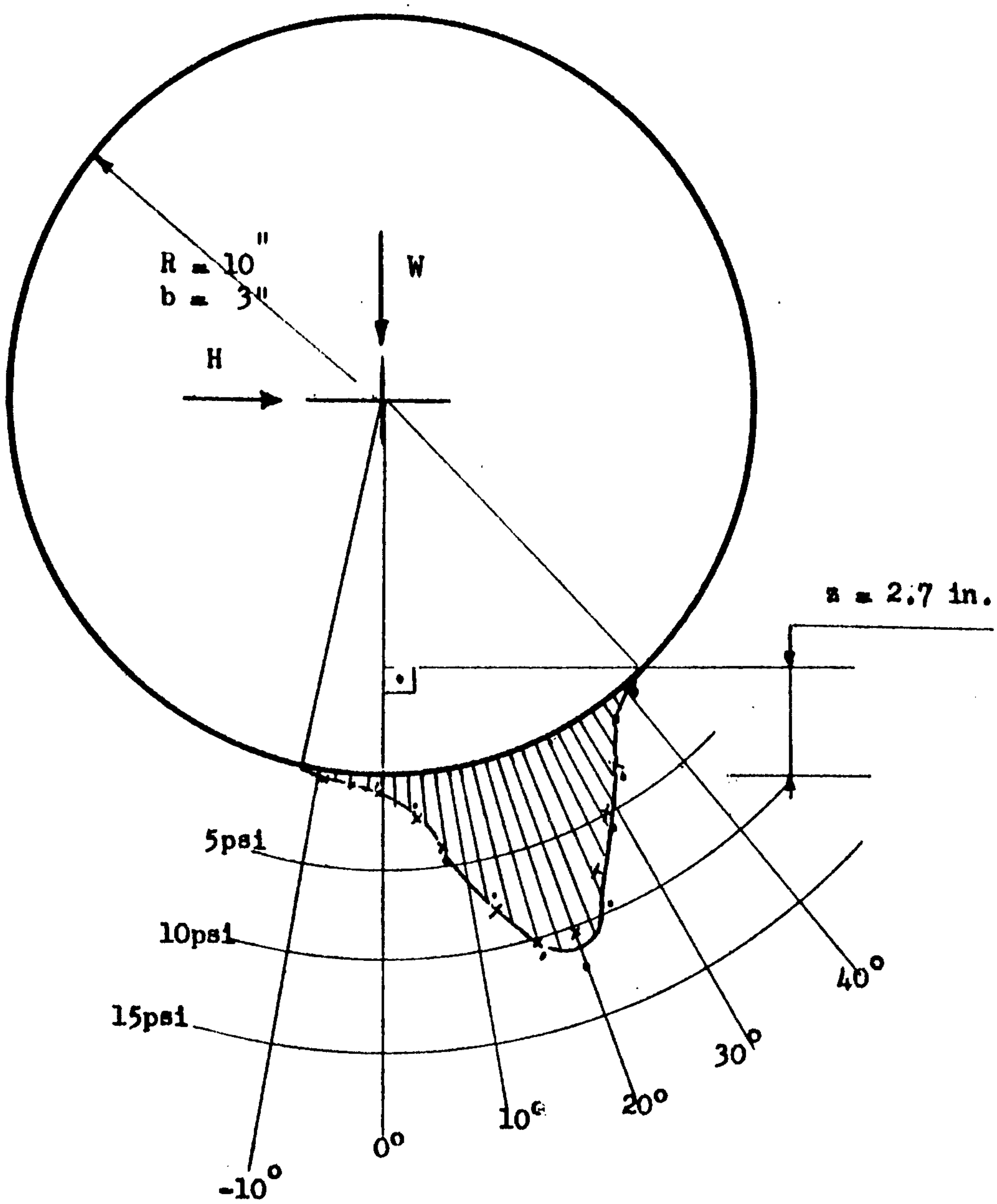


Figure No. 11.

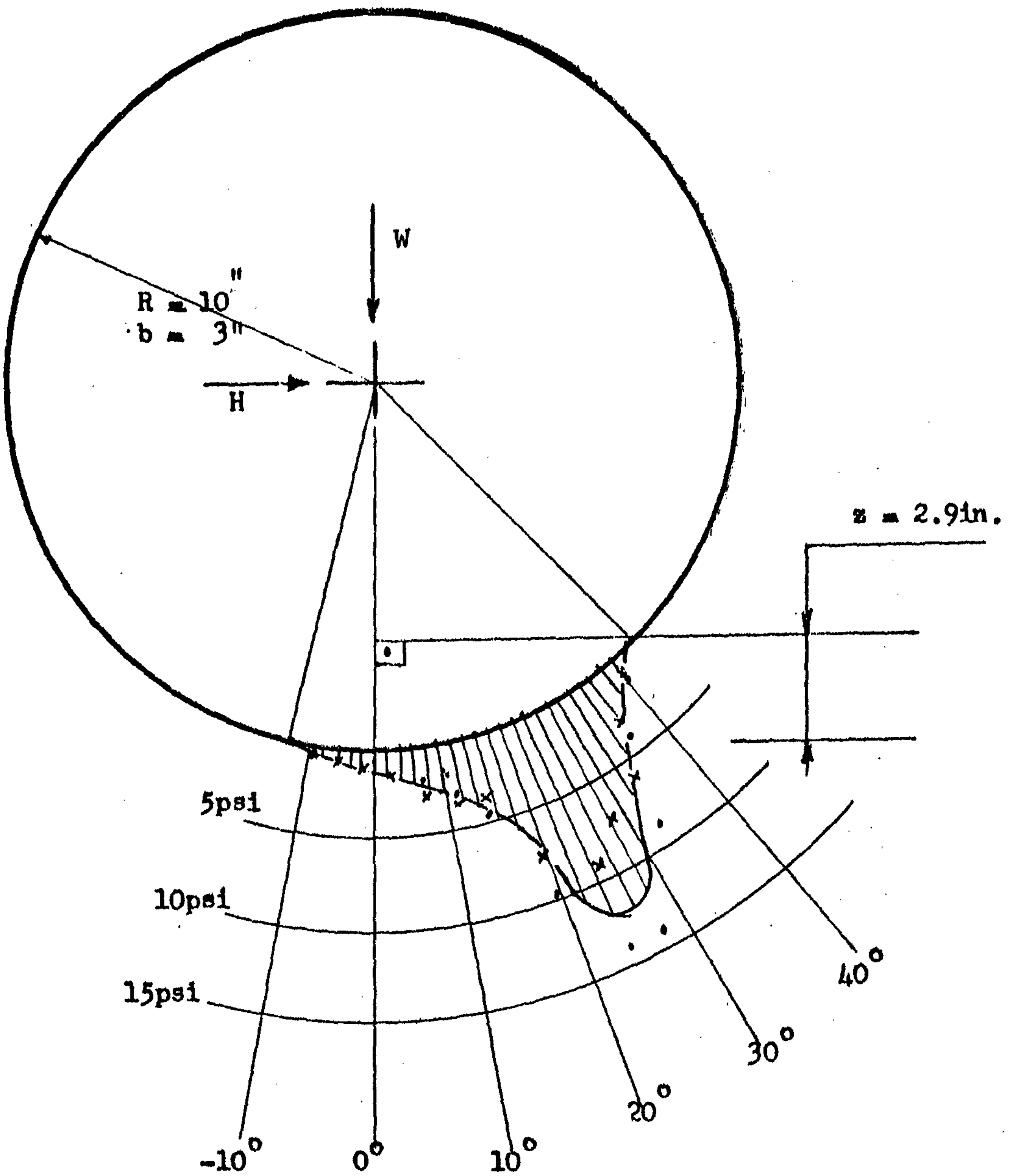
Pressure Distribution Under a Rigid Wheel in Sand at 150 Lbs Vertical Load and 56.3 % Slip.



Legend:
center •
outside ×

Figure No. 12

Pressure Distribution Under a Rigid Wheel in Sand at 150 Lbs Vertical Load and 100 % Slip.



Legend:
center •
outside x

Figure No. 13.

Pressure Distribution under a Rigid Wheel in Sandy-loam at 150 lbs. Vertical Load and 0% Slip.

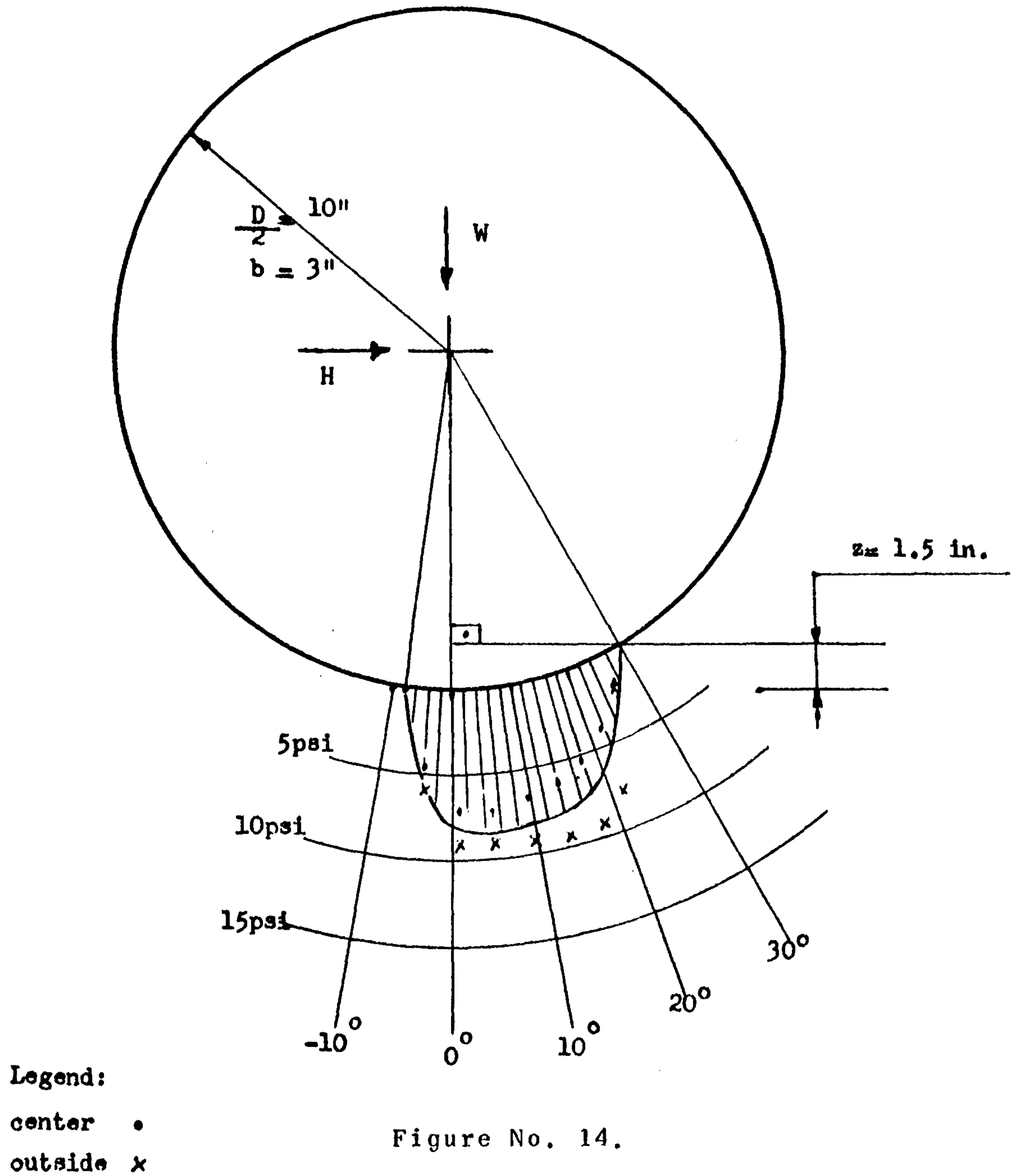


Figure No. 14.

Pressure Distribution under a Rigid Wheel in Sandy-loam at 150 lbs. Vertical Load and 39% Slip.

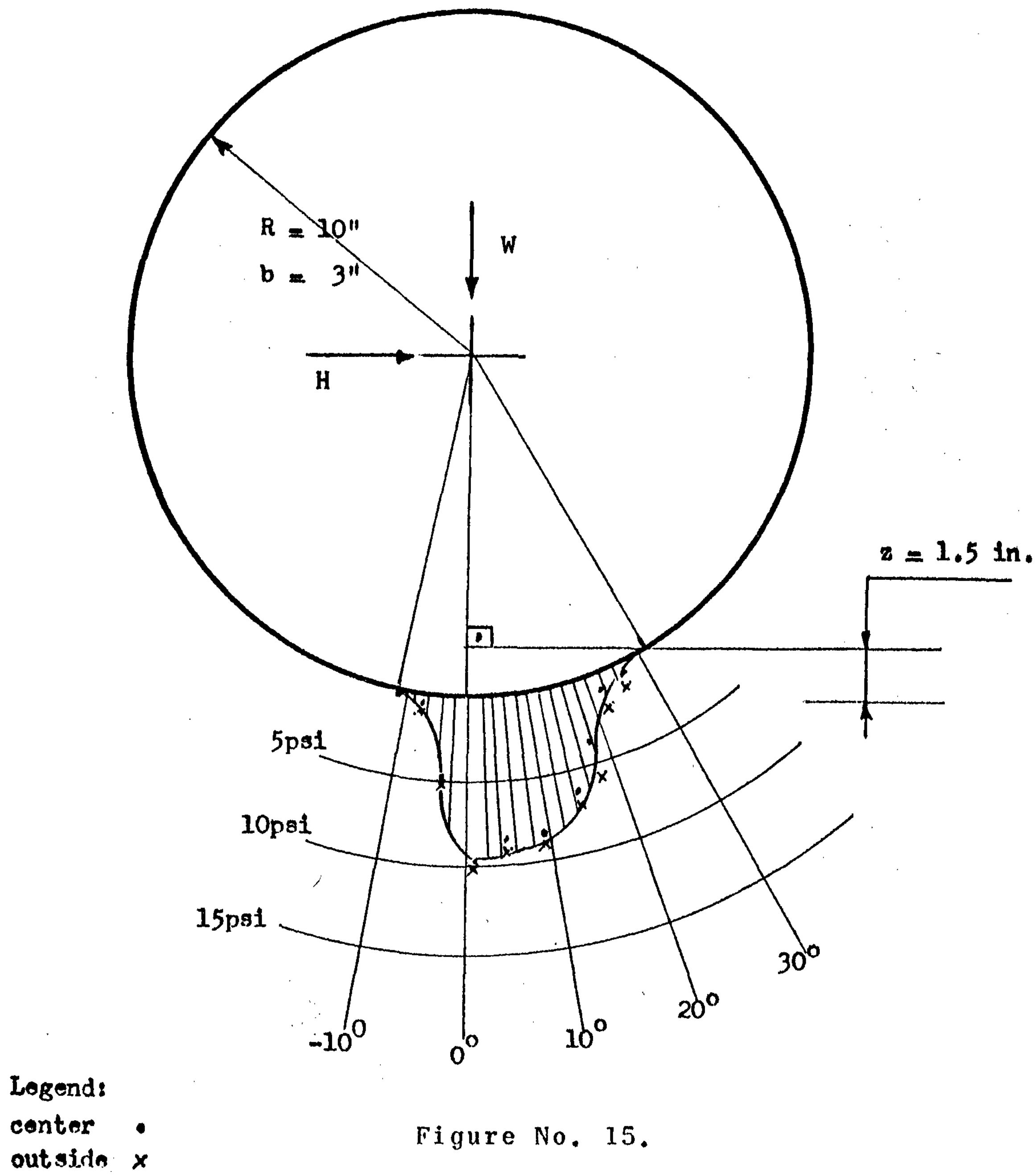


Figure No. 15.

Pressure Distribution under a Rigid Wheel in Sandy-loam at 150 lbs. Vertical Load and 100% Slip.

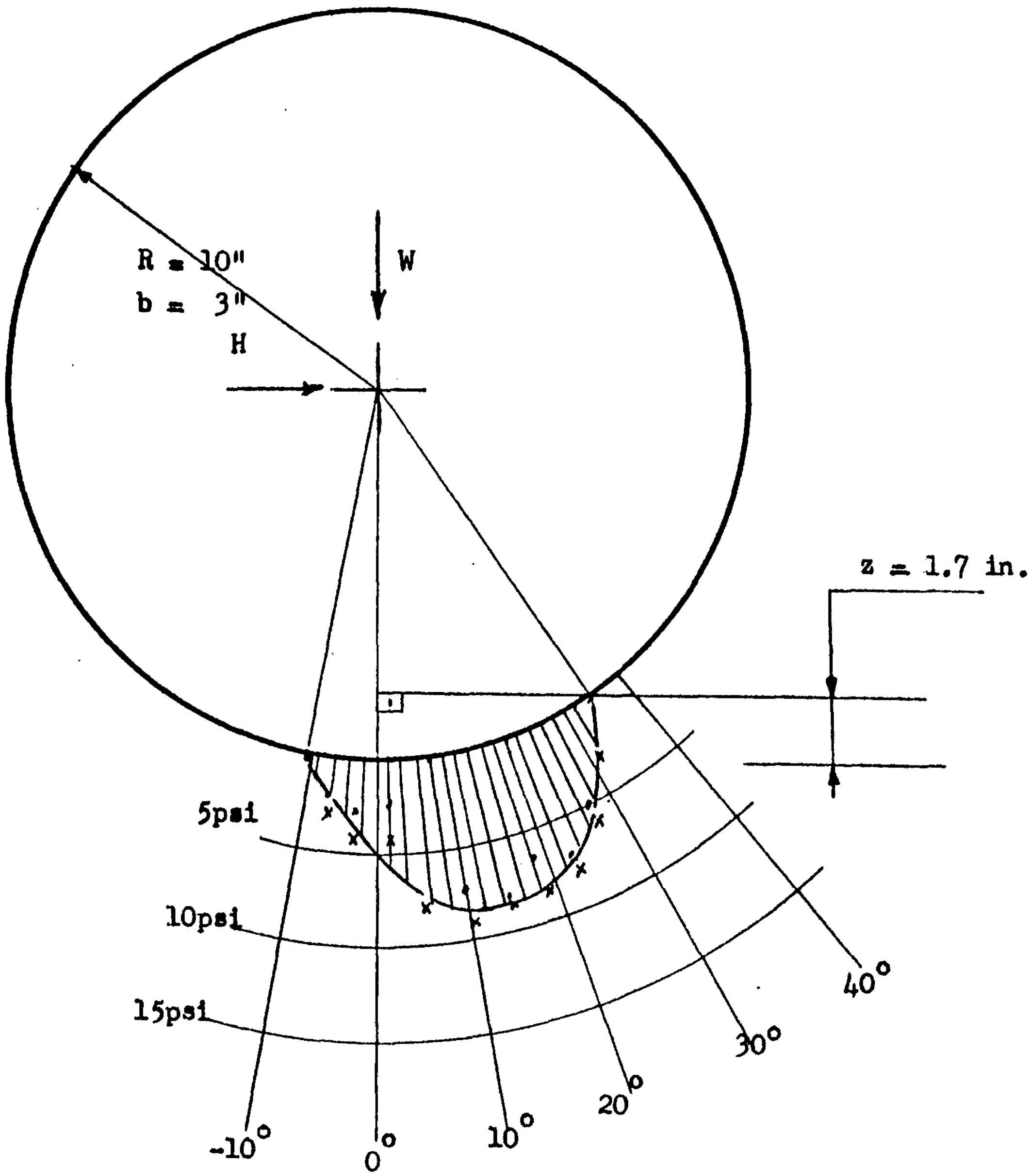
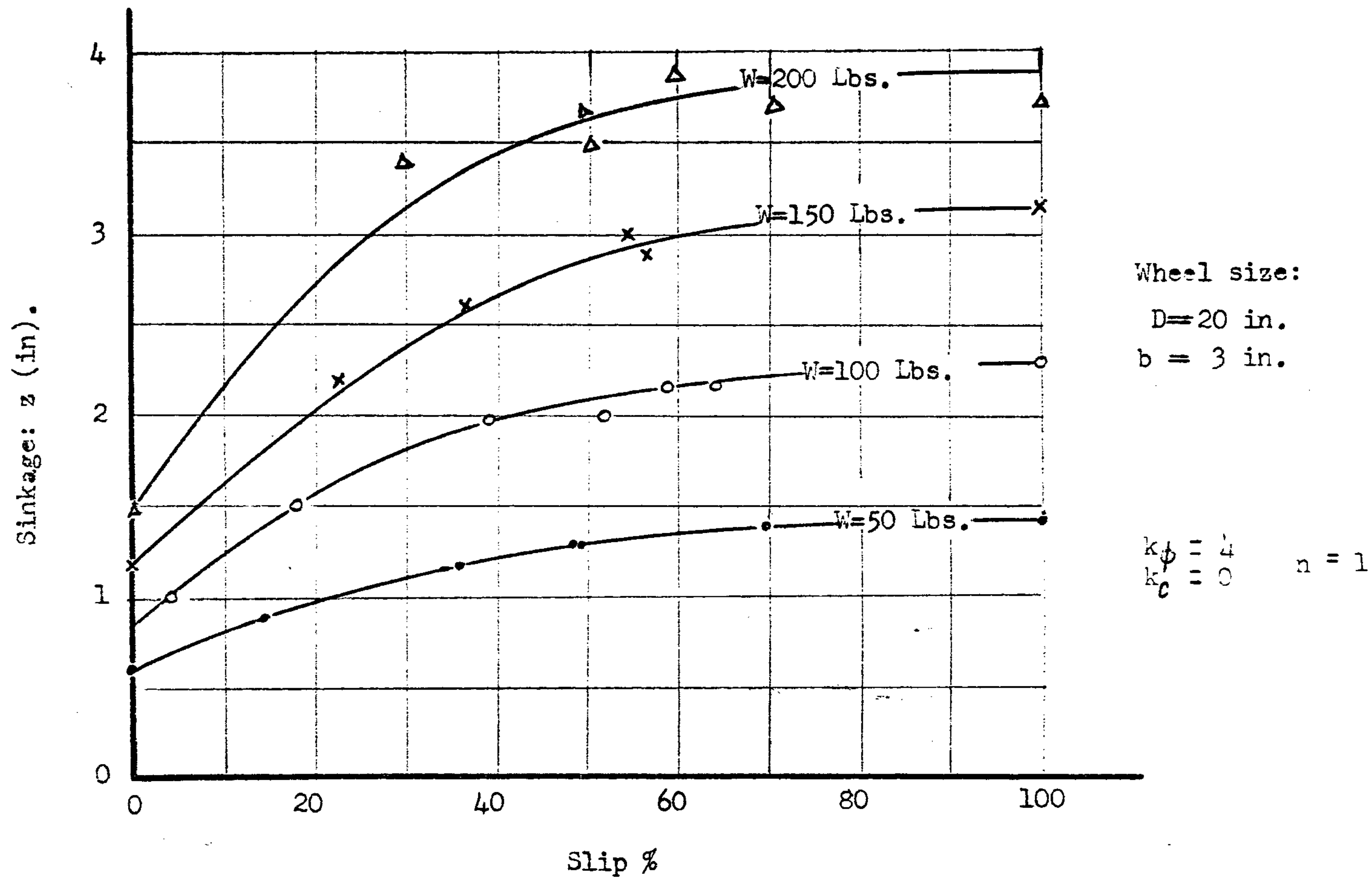


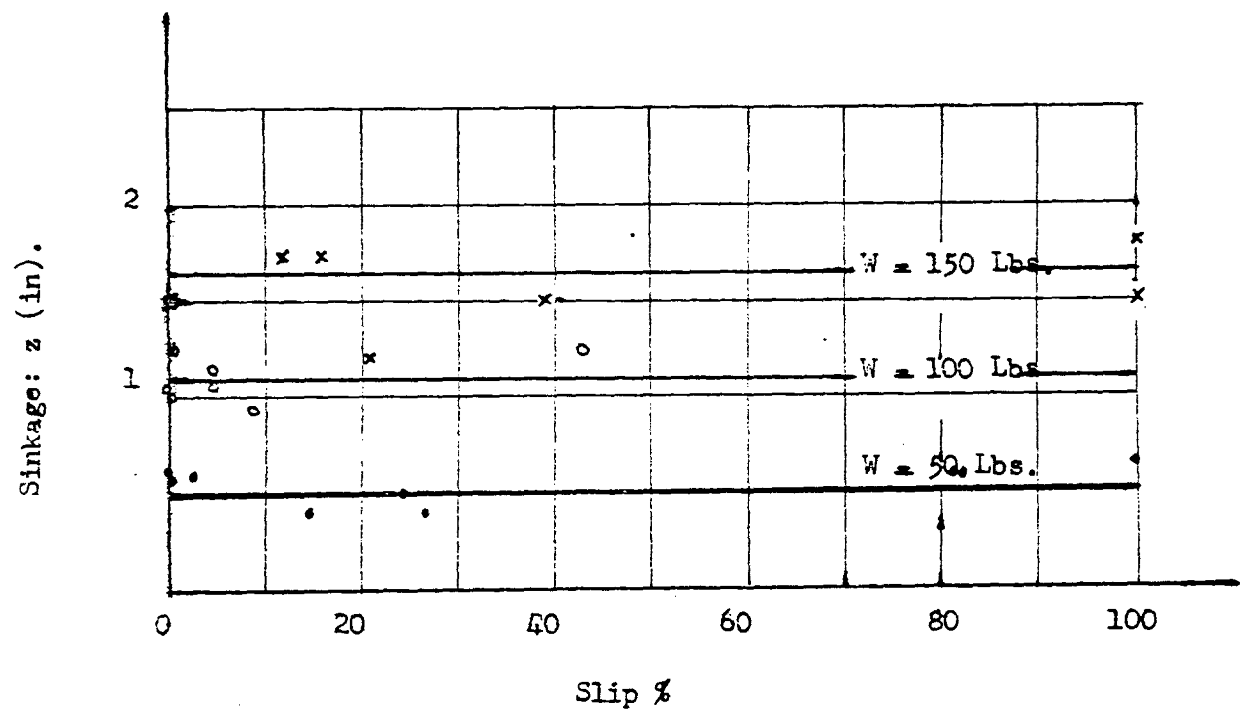
Figure No. 16.

Legend:
center •
outside x



Sinkage as a Function of Slip with Load as Parameter in Sand.

Figure No. 17.



Wheel size:

D = 20 in.

b = 3in.

Sinkage as a Function of Slip with Load as Parameter in Sandy-loam.

Figure No. 18.

Angular Position of the Normal Force as a Function of Slip in Dry-Sand.

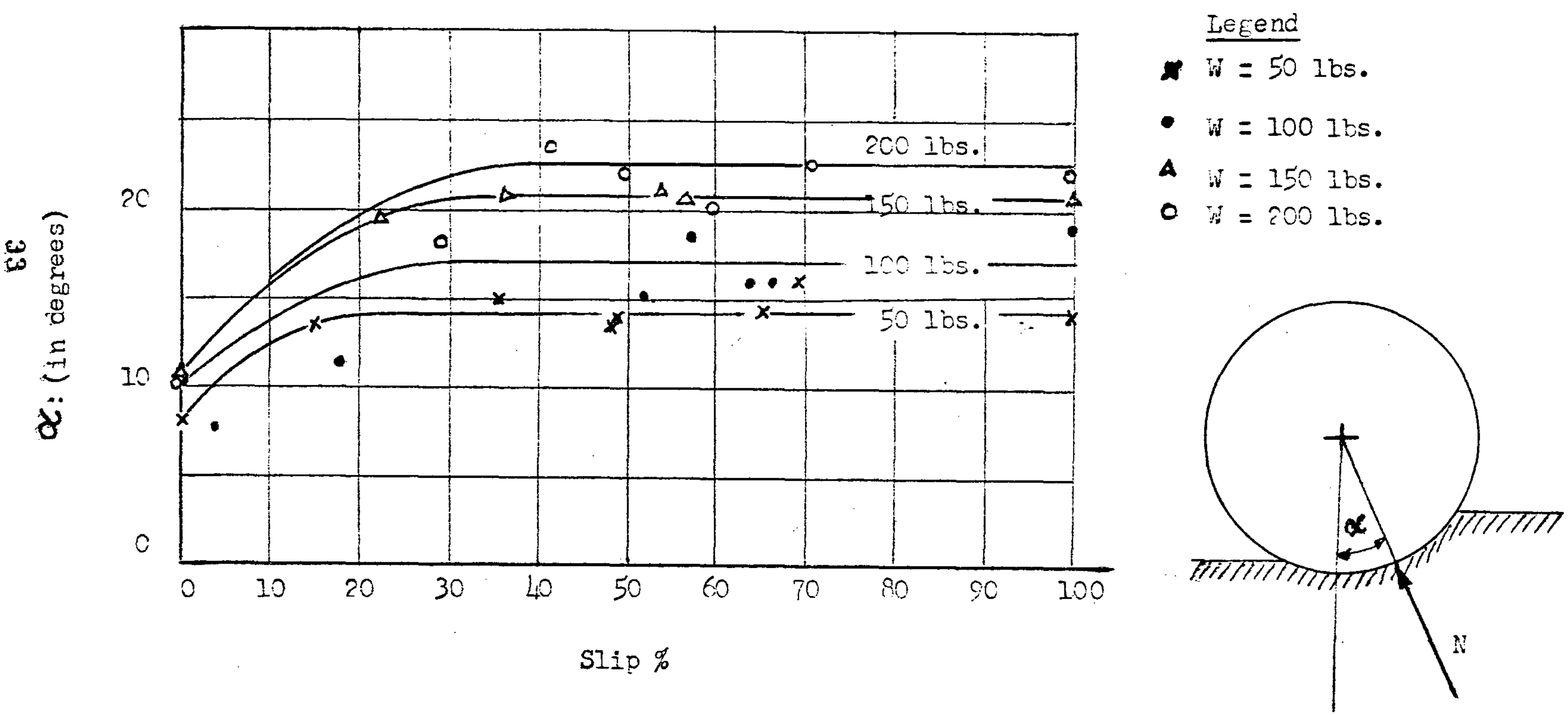


Figure No. 19.

Angular Position of the Normal Force as a Function of Slip
in Sandy-Loam.

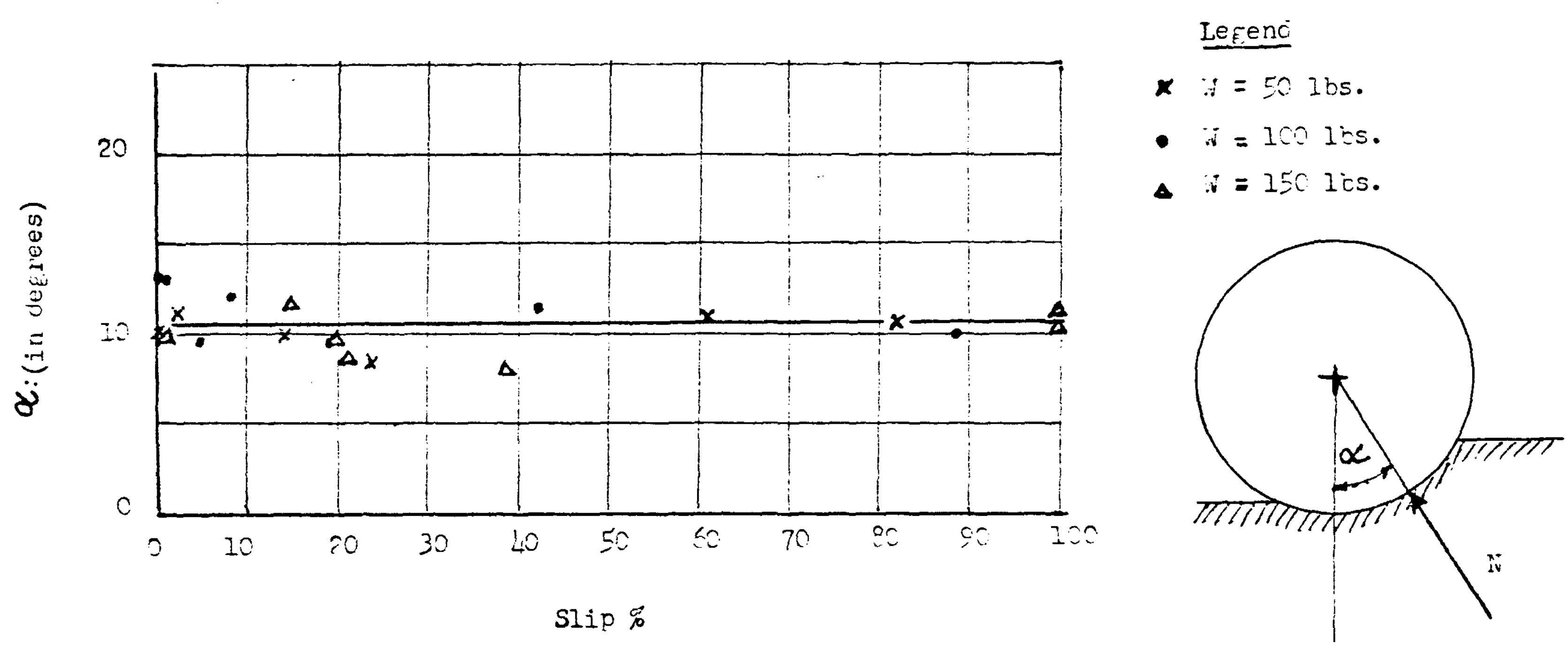
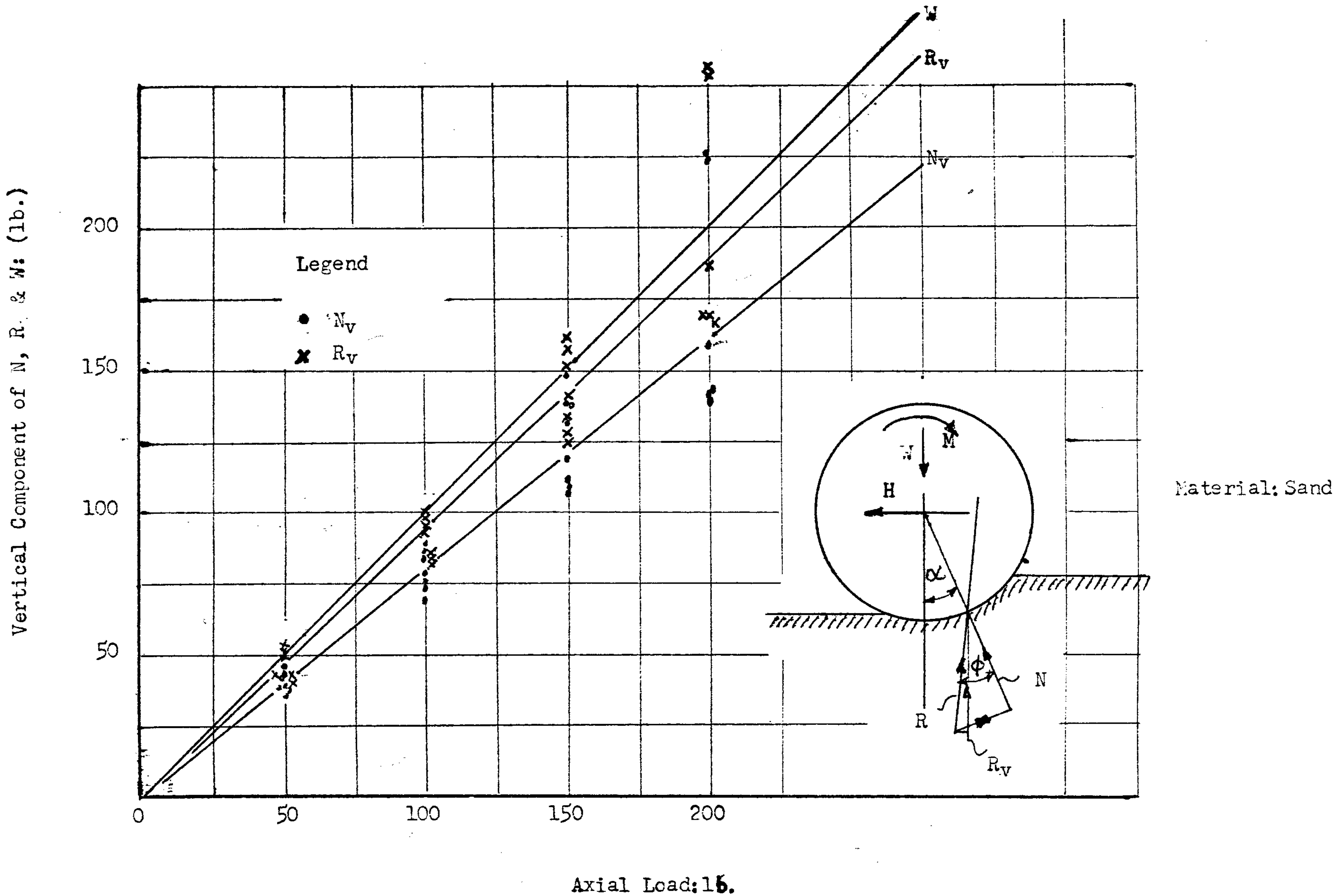


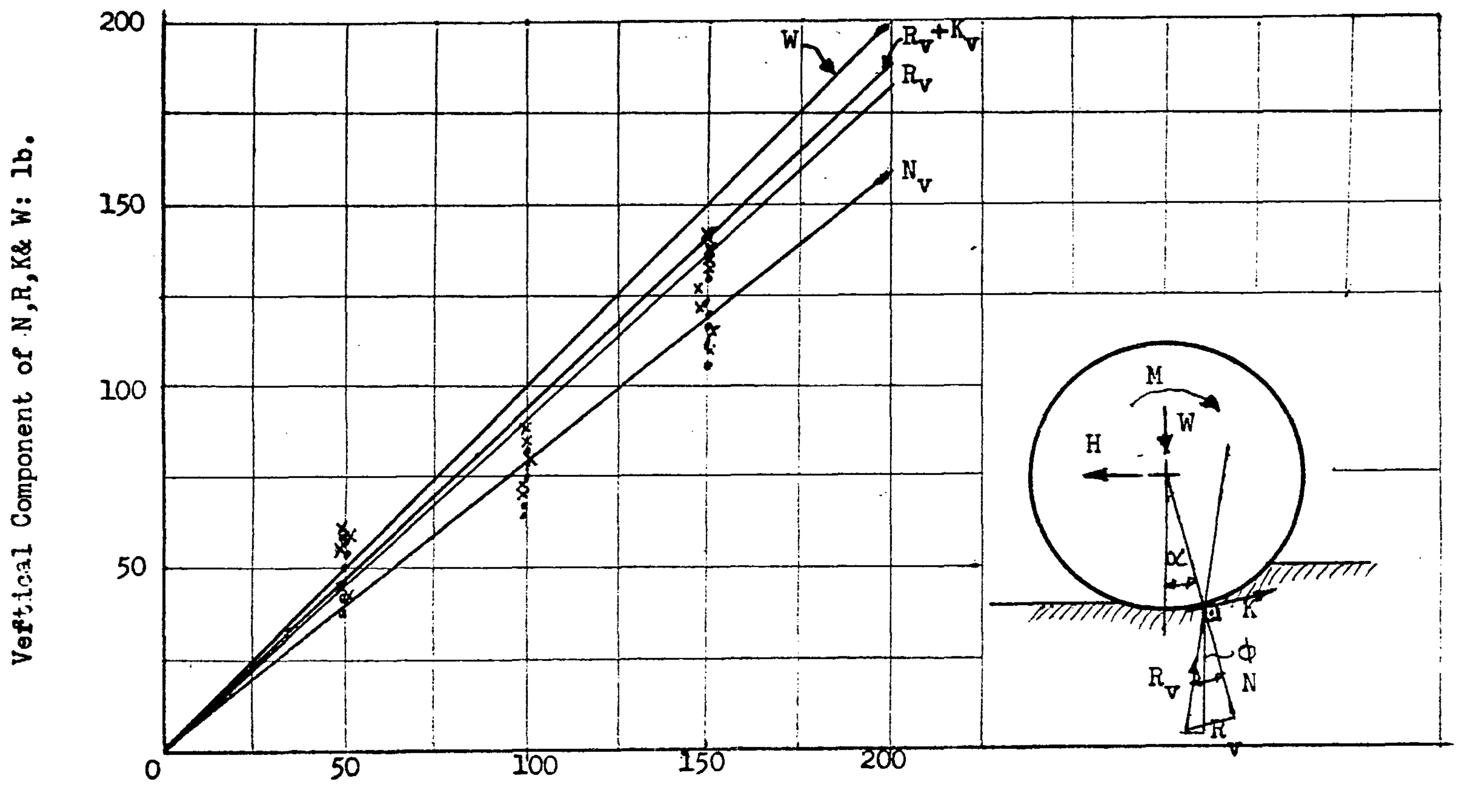
Figure No. 20.



Vertical Component of N, R, W, as a Function of the Axial Load in Sand.

Figure No. 21.

Material: Sandy-Loam.



Axial Load; lb.

Vertical Component of N, R, K and W, as a Function of the Axial Load in Sandy-Loam.

Figure No. 22.

Sliding Friction On Sand

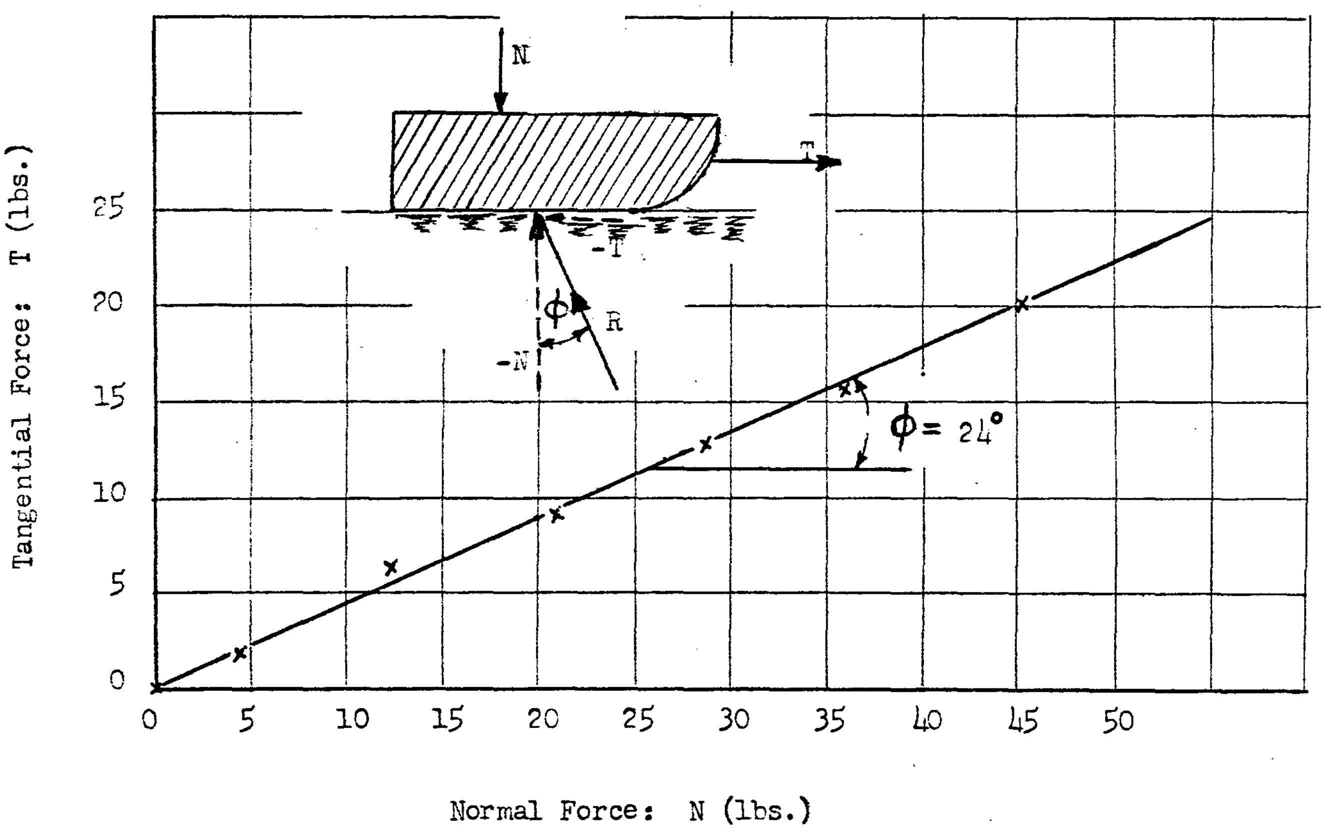


Figure No. 23.

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